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TOTAL ELECTRON CONTENT LUNAR VARIATION AT TWO MIDLATITUDE STATIONS

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Total electron content data of a year of the Ebro and Hamilton stations have been analyzed by the Chapman-Miller method and the components of the solar and lunar tides at both stations obtained. The same analysis has been performed with the data grouped by seasons. All results but the ones corresponding to Ebro equinoxes, are significant at the 5% level, and agree with results of other authors. The non-significance of the equinoxes results seems to be related to the location of the focus of the dynamo ionospheric currents. Also the semimothly lunar tide and its diurnal solar variation are obtained and the results are discussed.

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CONTENTS

INTRODUCTION.

Since Martyn (1947) determined the semidiurnal lunar tide of the F2 layer at Huancayo, many authors have been studing the lunar tide in the ionosphere (cfr. Matsushita (1967)). These studies are generaly made using the parameters of the different ionospheric layers such as the critical frequency, the virtual height or the height of the maximum of the layer. More recently, Huang (1978) made an analysis of the total electron content of the ionosphere (TEC) in order to study the semidiurnal lunar tide near the crest zone of the equatorial anomaly. Handa (1978) determined the solar dependence of the semimonthly lunar tide in fOF2 at Wakanaii and Kokubunji and sohws its agreement with the teoretical calculations made by Handa and Maeda (1978).

In the present work the semidiurnal lunar tide in TEC is determined for two stations and its variation is discussed. Also the semimonthly lunar tide is obtained and its dependence on solar time at different seasons as well as its seasonal variation are shown.

METHOD OF ANALYSIS AND DATA.

According to Chapman and Bartels (1940), the lunar variation of a geophysical parameter can be represented by

$$L=\sum_{n=1}^{\infty} l_n \sin((n-2)t+2\tau+\lambda_n) \qquad (1)$$

where t denotes solar time in hours, increasing from 0^h to 24^h from one local lower transit of the sun to next, τ denotes lunar time increasing from 0^h to 24^h from one local lower transit of the moon to the next, l_n denotes the amplitude of the n^{th} component of the lunar daily variation and λ_n its phase angle.

The second component, $l_2 \sin(2\tau+\lambda_2)$, is the most important one. It has a period of half a lunar day and is the only one purely lunar. All other components depend on both, lunar and solar time.

The lunar variations of many geophysical data, are masked by the much greater solar daily variations that depend only on solar time. They may be represented by

$$S=\sum_{p=1}^{\infty} s_p \sin(pt+\sigma_p)$$

were s_p and σ_p are the amplitude and phase of the p^{th} component.

As it is well known, Chapman and Miller (1940) developed a method of analysis that separates both kinds of variations and gives the amplitude and phase of the lunar components starting from the data given in solar time. The analysis gives also the solar components as a byproduct. We applied this method to the data of two stations (Ebro Observatory and Hamilton) in order to obtain the lunar components of the total electron content (TEC) variation.

The Ebro data consist of the hourly Faraday angles of the signal of the SIRIO italian satellite, recorded at the Ebro Observatory from December 1977 to November 1978. The satellite was located at 15ºW and the corresponding subionospheric point for Ebro and for a 420Km ionospheric height,was at 37.1ºN, 1.5ºW.

The Hamilton data were kindly supplied to us by Dr.Klobuchar. They are hourly TEC data obtained by the Faraday rotation method for 1976 and correspond to the subionospheric point 38.7ºN, 70.7ºW.

RESULTS AND DISCUSSION.

DIURNAL VARIATION.

The analysis has been applied, first of all, to the values of the whole year, rejecting only the data of the days in which at least one hourly value was missing. Afterwards,a

similar analysis was applied to the data grouped in accordance with the three seasons: winter, equinoxes and summer. The results are shown in tables I and II, where the amplitudes and phases of the solar and lunar components, with their probable errors appear. The percentages of the amplitudes, also given in the tables, are related to the mean value of the data considered in each analysis.

According to Leaton et al. (1962), the amplitude is to be considered significantly different from zero at the five per cent level if it is greater than 2.08 times its probable error. As can be seen all the solar terms, at both stations, for all distributions of data, fulfil this condition, so that are significant.

Among the lunar components, in Ebro, the first harmonic is significant only in winter and when the data of the whole year are considered. The second harminic is always significant except in the equinoxes, when no lunar harmonic is significant. The third and fourth harmonic are only significant in summer.

In Hamilton, the first lunar component is significant in all distributions but the summer one. The second component is significant in all distributions. The third component is significant when the data are grouped by seasons, but is not significant if all the data are taken together. Lastly, the fourth component is significant in winter and summer.

The amplitude of the lunar components is always very small, as shown in tables I and II. A great amount of data is needed to determine them with enough confidence. The number of data analyzed in this paper, (a maximum of 245 days for Ebro and 395 days for Hamilton) allows us to give only provisional results in spite of the fact that the probable errors indicate, in many cases, that the results are significant. This fact has to be kept in mind in all the following discusion.

Fig. 1 a-d, show the harmonic dials of each lunar component for the two stations and for the different distributions of data, with the corresponding circles of probable errors.

ALL DATA

Harm.	Solar terms: Amplitude %	Val.	p.err	Phase °	Lunar terms: Amplitude %	Val.	p.err	Phase °
1	59	417.	6.3	242.9	2	19.4	6.9	359.2
2	9	69.4	3.0	80.9	2	14.0	3.2	135.9
3	4	34.7	2.5	36.2	-	3.1	2.6	290.7
4	1	12.6	1.8	321.2	-	1.1	1.8	357.1

WINTER

Harm.	Solar terms: Amplitude %	Val.	p.err	Phase °	Lunar terms: Amplitude %	Val.	p.err	Phase °
1	83	395.	10.7	256.6	7	36.5	11.7	356.9
2	27	123.	4.9	80.7	4	21.2	5.1	145.7
3	5	26.0	3.5	25.9	1	5.3	3.6	293.1
4	6	32.3	1.7	263.3	-	2.0	1.8	146.5

SUMMER

Harm.	Solar terms: Amplitude %	Val.	p.err	Phase °	Lunar terms: Amplitude %	Val.	p.err	Phase °
1	39	307.	7.3	228.5	1	12.1	8.0	36.6
2	3	26.5	4.4	171.3	2	15.7	4.7	152.5
3	1	14.4	2.6	33.5	1	9.4	2.7	297.2
4	4	32.8	2.4	30.9	1	8.6	2.5	24.9

EQUINOXES

Harm.	Solar terms: Amplitude %	Val.	p.err	Phase °	Lunar terms: Amplitude %	Val.	p.err	Phase °
1	70	589.	8.3	242.4	-	7.2	9.1	209.1
2	11	96.8	5.8	62.8	-	6.6	6.1	30.7
3	8	67.5	4.9	40.7	-	4.9	5.1	110.5
4	1	12.8	3.7	279.7	-	5.1	3.8	209.1

Table I.- Solar and luni-solar harmonics of the T.E.C. at Ebro. Amplitude units in degrees of the Faraday angles.

ALL DATA

	SOLAR TERMS				LUNAR TERMS			
Harm.	Amplitude			Phase	Amplitude			Phase
	%	Val.	p.err	º	%	Val.	p.err	º
1	73	43.3	0.35	242.0	1	1.0	0.38	35.4
2	5	3.3	0.31	91.3	3	2.0	0.32	162.1
3	6	4.0	0.15	13.9	-	0.3	0.15	320.3
4	1	0.9	0.10	19.4	-	0.2	0.11	279.9

WINTER

	SOLAR TEMS				LUNAR TERMS			
Harm.	Amplitude			Phase	Amplitude			Phase
	%	Val.	p.err	º	%	Val.	p.err	º
1	83	44.1	0.65	253.7	2	1.5	0.71	66.6
2	28	15.3	0.40	61.6	2	1.4	0.42	203.3
3	4	2.3	0.26	327.8	1	0.8	0.27	13.9
4	5	3.0	0.19	211.4	-	0.4	0.19	158.4

SUMMER

	SOLAR TERMS				LUNAR TERMS			
Harm.	Amplitude			Phase	Amplitude			Phase
	%	Val.	p.err	º	%	Val.	p.err	º
1	62	39.7	0.59	229.9	-	0.4	0.65	6.5
2	16	10.6	0.40	223.5	2	1.9	0.42	140.9
3	8	5.2	0.26	23.7	1	0.6	0.27	168.1
4	6	4.3	0.20	27.8	1	0.7	0.21	280.4

EQUINOXES

	SOLAR TERMS				LUNAR TERMS			
Harm.	Amplitude			Phase	Amplitude			Phase
	%	Val.	p.err	º	%	Val.	p.err	º
1	78	48.1	0.60	242.0	2	1.5	0.66	11.6
2	7	4.5	0.52	81.4	5	3.1	0.54	158.2
3	8	5.3	0.30	21.5	1	0.9	0.31	303.6
4	2	1.3	0.16	17.6	-	0.4	0.17	347.4

Table II.- Solar and luni-solar harmonics of T.E.C. at Hamilton. Amplitude units in elect./sq.meters*10**15

The dial corresponding to the equinoxes for Ebro has been omitted because none of the components are significant.

Comparing the results of both stations, we see that, for the data of the whole year (fig. 1.a), the Hamilton lunar components appear rotated about 30º counter-clockwise with respect to those of Ebro. Only the non-significant fourth component is an exception. The winter components (fig. 1.b)show also a counter-clockwise rotation but the angle rotated is much bigger. It is about double for the first two harmonics and nearly three times for the third one. In summer (fig.1.d), the rotation is clockwise but the angles rotated are very different from one component to another.

Many authors give the phase of the lunar components as the time at which the maximum variation occurs. The dials of fig. 1,a-d give also that time if the origen is taken on the vertical 90º angle and the time rekoned clockwise. The time scale is different for the different components. A variation of 2π radians corresponds to a change of 24 hours for the first component, 12 hours for the second one,8 hours for the third one and 6 hours for the fourth one. As can be seen in figs. 1.a-d, the phase of the second harmonic oscilates between 8 h. and 10.5hr. lunar time, that are inside the range of values generally found at middle latitudes for the lunar variation of foF2 (cfr. Matsushita (1967), Handa (1978), etc.).

If we compare the amplitude of the second lunar component of each station for different seasons, we see that in Ebro, in winter is slightly larger than in summer. In Hamilton, on the contrary, the amplitude in summer is slightly greater than in winter, being the maximum one in the equinoxes.

Matsushita (1967) found for the second lunar component of the foF2 variation that the amplitude in local summer is usually larger than in local winter. This agrees with the results of Hamilton. Nevertheless he also reports results of two stations that agree with the results of Ebro. On the other hand Shatten and Mendillo (1980) found that the lunar effect on TEC in winter at two midlatitude stations is larger than in

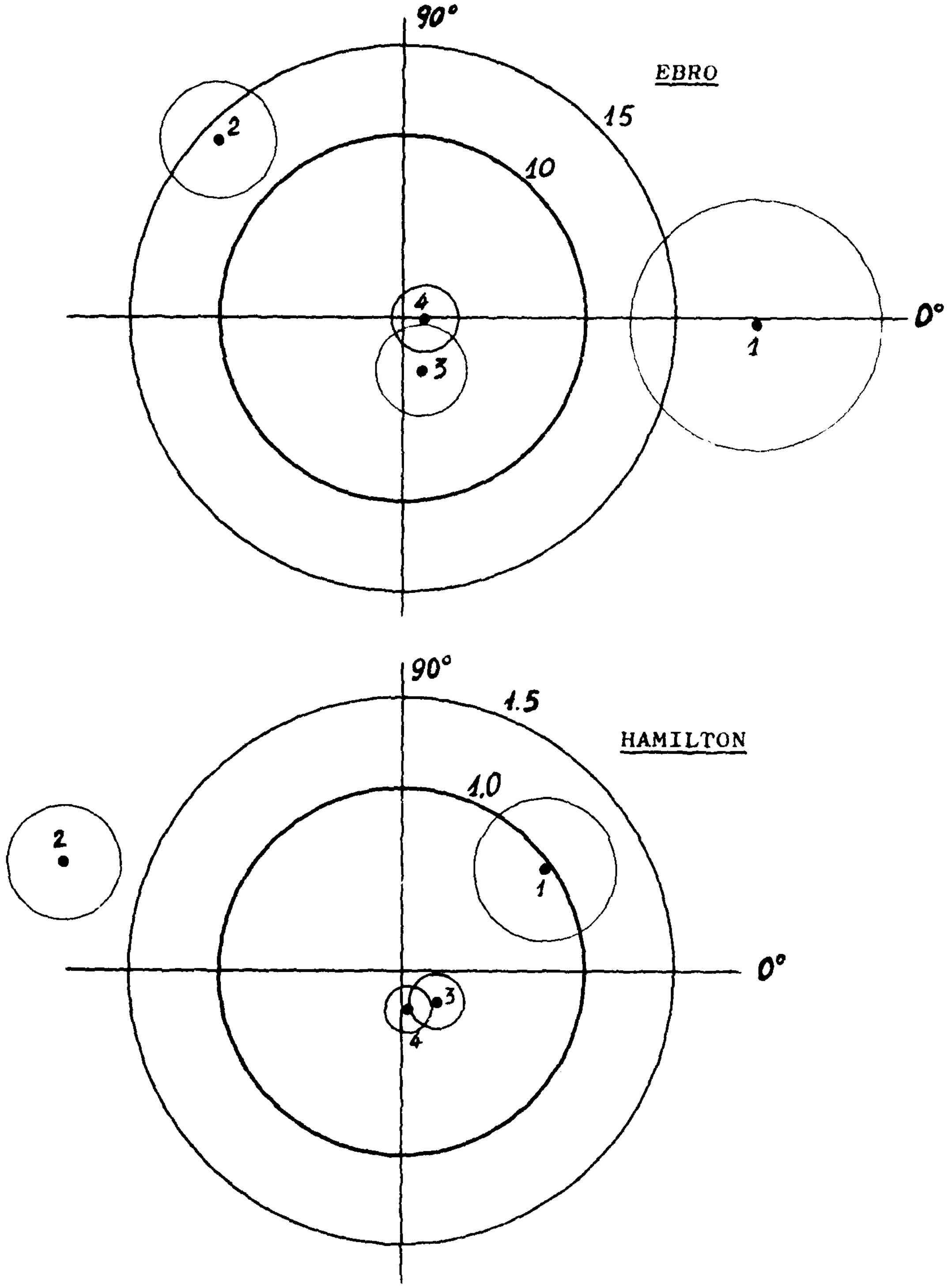


Fig.1a.- Lunar harmonics for data of one year

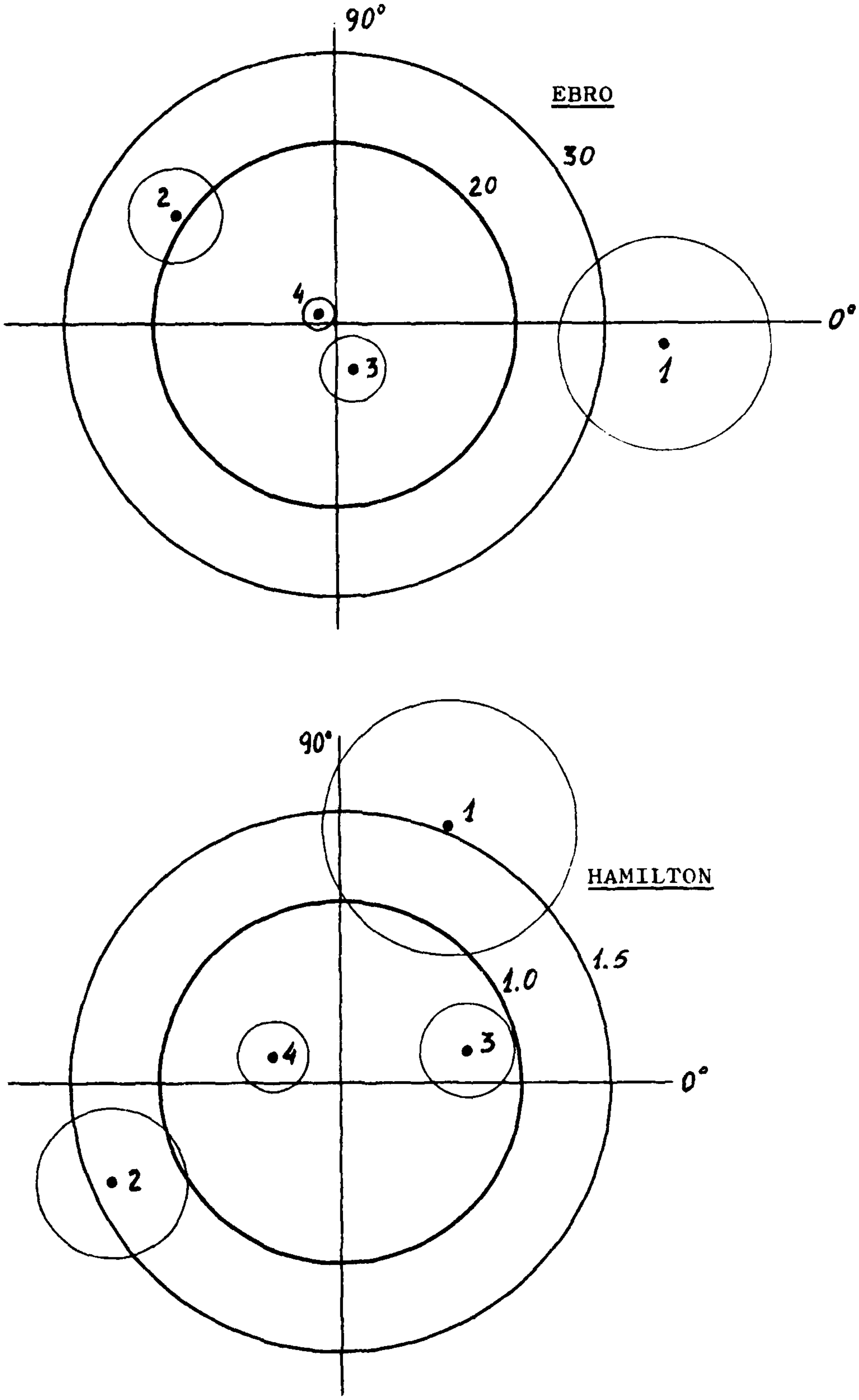


Fig.1b.- Lunar harmonics for winter data

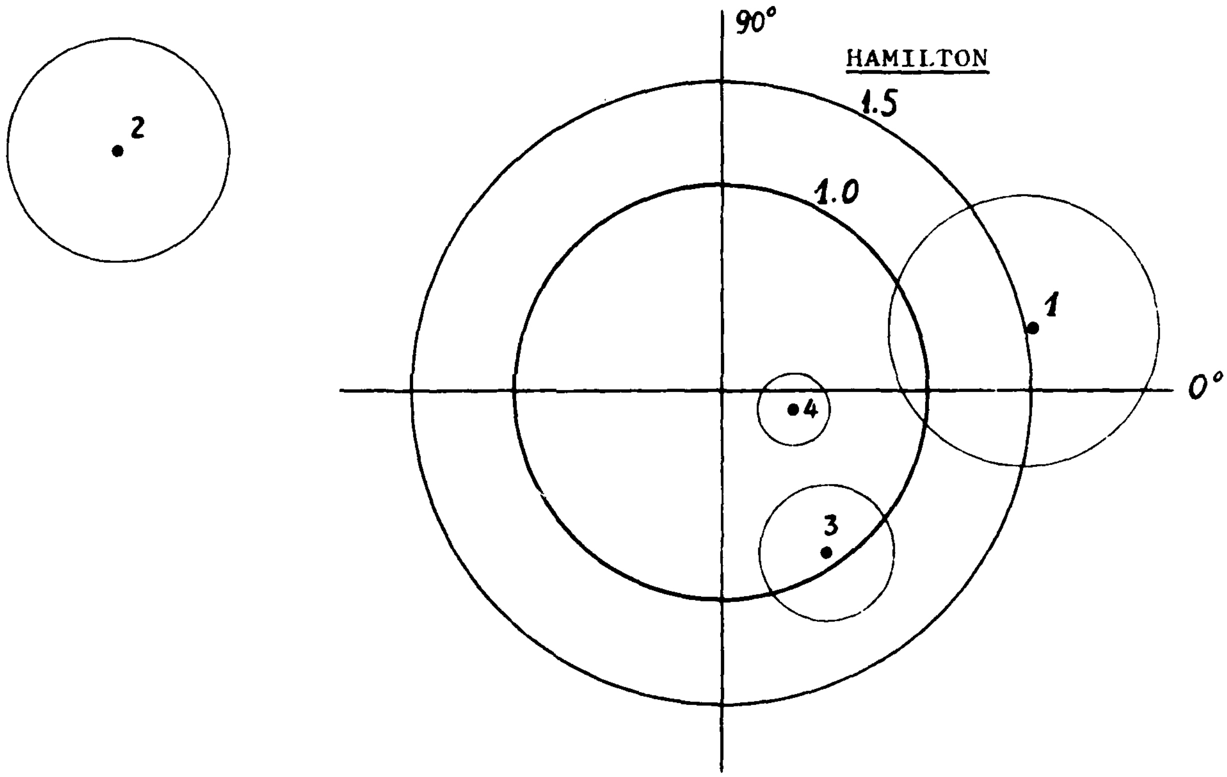


Fig.1c.- Lunar harmonics for equinoxes data.

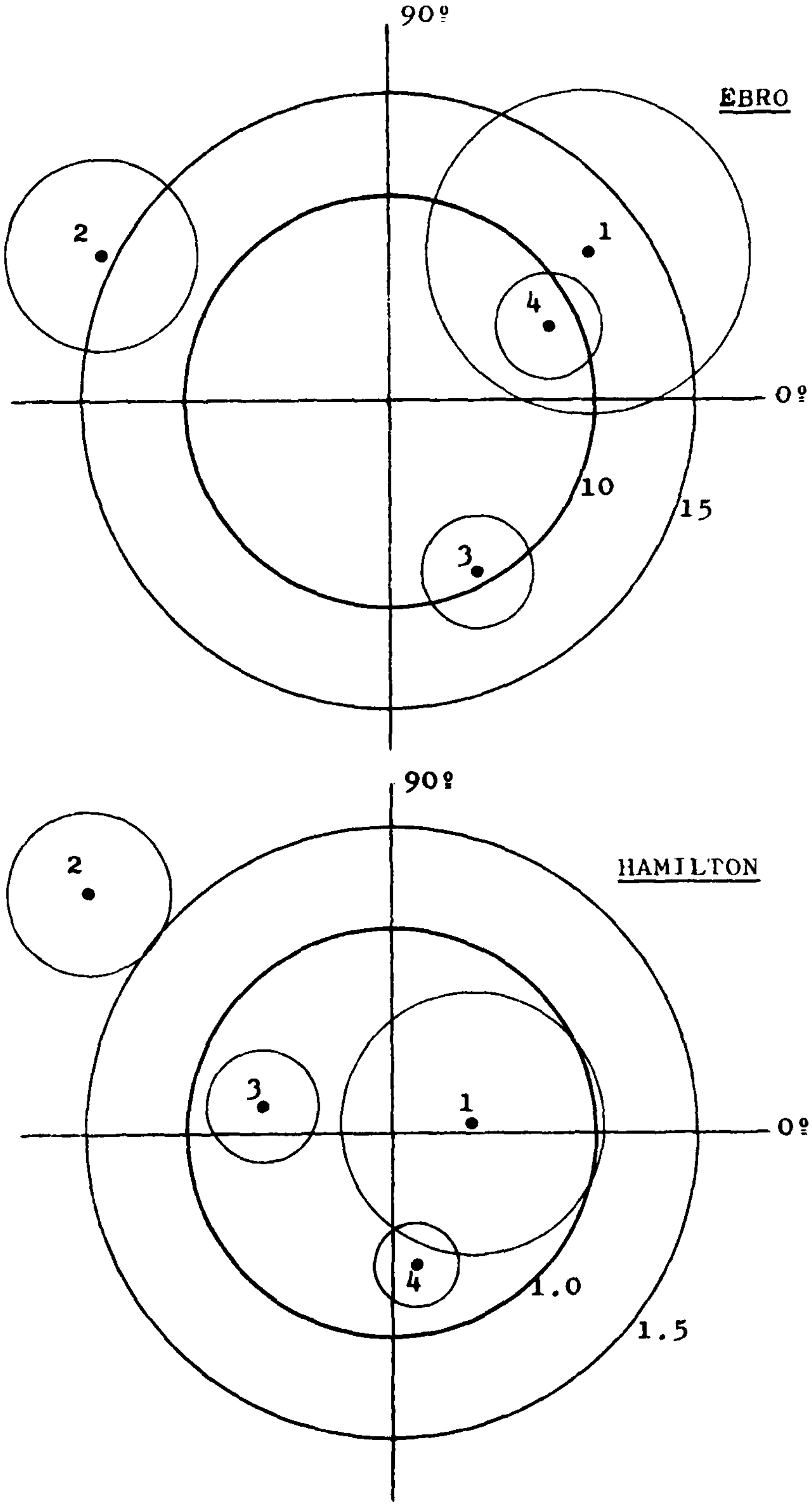


Fig.1d.- Lunar harmonics for summer data

summer.

The influence of the moon on the F2 ionospheric layer has been interpreted se produced by an electromagnetic drift of the layer caused by the superposition of a small electrostatic field(lunar) on a large (solar) field. (cfr. Abur-Robb and Dunford (1975)).

Handa and Maeda (1978) calculated the lunar effect on the F2 layer assuming that the electric fields that produce the drift, are the solar and lunar electric fields in the E-region deduced from the solar and lunar geomagnetic variations observed on the ground. The Ebro Observatory is very near the focus of the current system associated with these fields, so that the daily variation of the horizontal magnetic component, can be very different for different days, (as is shown in fig. 2), depending on the location of the focus relative to the station. As it is known since Hasegawa, the latitude of this focus changes from day to day,although its mean position remains about 40°latitude. Moreover, the summer mean daily variation of the horizontal magnetic component in Ebro corresponds to a station located north of the focus, while the winter mean variation corresponds to a station south of the focus. The equinoctial variation corresponds to the superposition of the other two. This is shown in fig.3 where the mean daily variation of the H geomagnetic components for ten years at Ebro is shown for the different seasons. It looks like if at equinoxes, the focus of the current, were some times at the north of the station and some times at the south of the station, so that the mean daily variation of the magnetic component is not much representative of the real daily variation of the component.It is possible that the non significance of the equinoctial lunar components of TEC variation at Ebro, could be due to this cause, since the variation of the electrostatic field that produces the ionospheric drift, can be deduced from the variation of the magnetic components at ground.

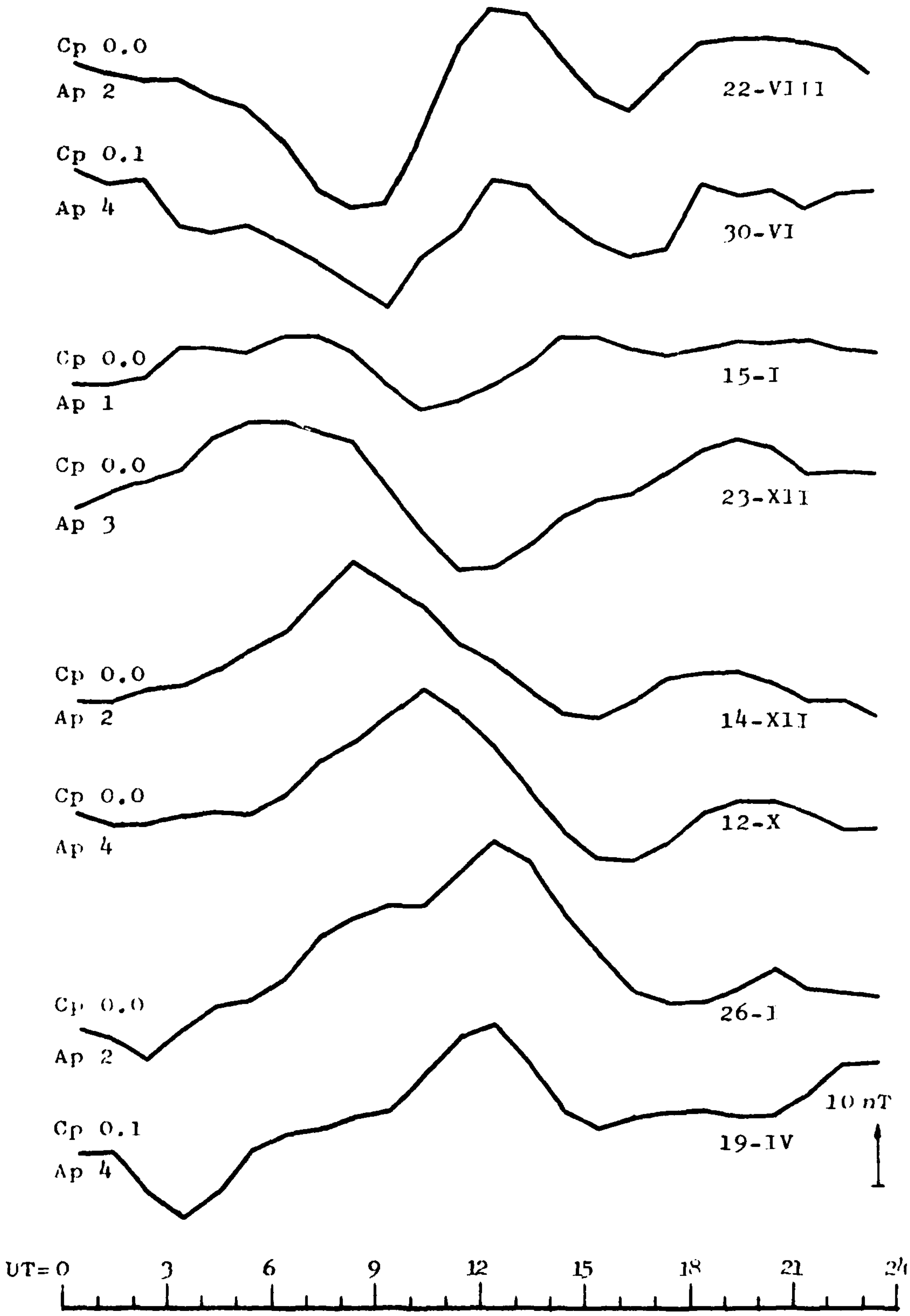
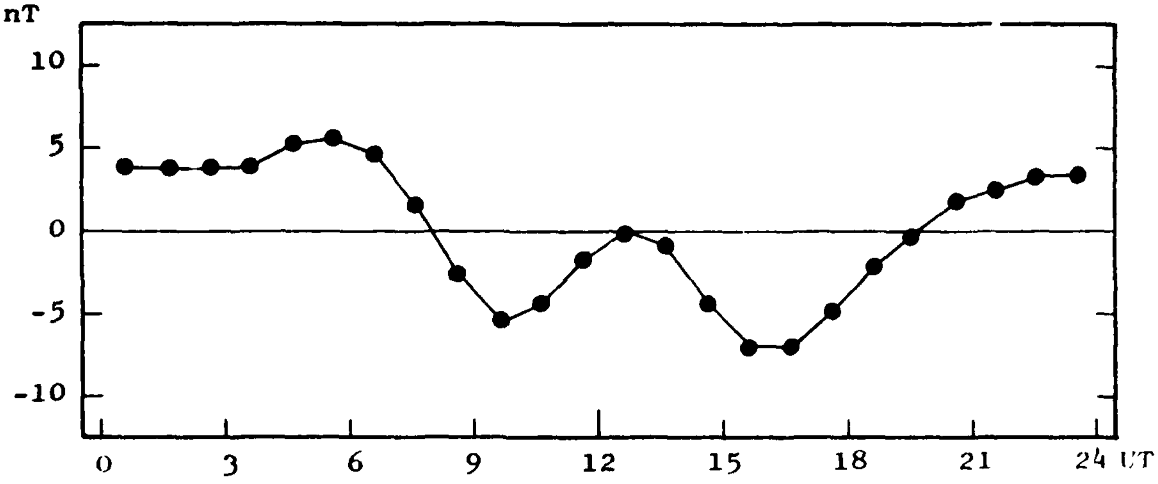


Fig. 2.- Daily variation of the H magnetic component at Ebro on eight quiet days (1955); Ci = 0.0



Mean diurnal variation of the H magnetic component at Ebro for ten years (1950-1959)

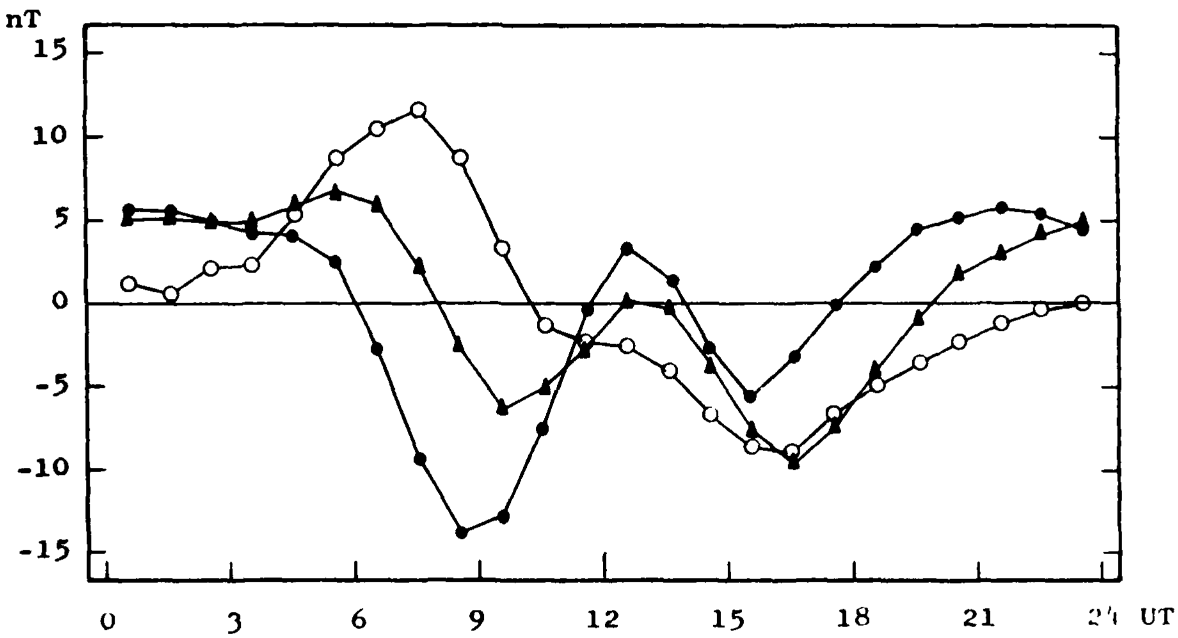


Fig. 3.- Mean diurnal variation of the H magnetic component at Ebro in Winter (○), Equinoxes (▲) and Summer (●) for the period 1950-1959

SEMIMONTHLY LUNAR VARIATION.

The semimonthly lunar variation has been obtained from the results found for the lunar harmonics of the different seasons. As it is well known, for the first four harmonics eq. 1 can be written.

$$L=\sum_{1}^{4} l_n \sin(nt-2\nu+\lambda_n) \qquad (2)$$

where $\nu=t-\tau$ indicates the phase of the Moon, measured by the hour angle between the Moon and the Sun, increasing from 0^h at one new Moon to 24^h at the next.

For the fixed solar time, ti, eq. 2 can be written

$$L_i=-\sin 2\nu \sum_{1}^{4} l_n \cos\varphi_{i_n} + \cos 2\nu \sum_{1}^{4} l_n \sin\varphi_{i_n}$$

where

$$\varphi_{i_n}=nt_i+\lambda_n$$

There-fore the amplitude and the phase of the semimonthly lunar variation at the solar time ti $(L_{s_i}\cos(2\nu-\Phi_i))$ are respectively

$$L_{s_i}=((\sum_{1}^{4} l_n \sin\varphi_{i_n})^2+(\sum_{1}^{4} l_n \cos\varphi_{i_n})^2)^{1/2}$$

$$\Phi_i=tg^{-1}((-\sum l_n \cos\varphi_{i_n})/(\sum l_n \sin\varphi_{i_n})) \qquad (3)$$

that depend on t_i through φ_{in}.

We used eqs. 3 to deduce the amplitude and phase of the semimonthly lunar variation for every solar hour at Ebro and at Hamilton. The input values are the amplitude and pha se of the diurnal lunar components, previously obtained for the two stations by the Chapman-Miller method. The results sre shown in fig. 4, a-d.

Amplitude.

As it can be seen, the amplitude shows a similar daily variation at both stations in all but the equinoxes curves: A maximum in the afternoon or evening and a minimum near the early hours. In summer at both stations and in equinoxes at Ebro both, a second maximum and minimum appear.

When the whole year is considered, the maximum takes place at 1500LT in Ebro and, perhaps, an hour later in Hamilton. The minimum, on the contrary, occurs in Ebro later (0400)than in Hamilton (0300). Looking at the different seasons we can say that in both stations the time of the maximum shifts towards later hours from winter to summer. The minimum has not a clear evolution. In Ebro it looks like if the time of minimum shifts from the early hours of the day in winter to one or two hours before midnight in summer. In Hamilton the shift is also towards earlier hours but smaller than in Ebro. At equinoxes in Ebro appears a secondary maximum at about 0800LT that produces a secondary minimum at about 1100LT. In summer at the same station the secondary maximum takes place near 0200LT, and the secondary minimum at about 0500LT. In Hamilton the secondary maximum appears only in summer at about 0800LT, with the corresponding minimum at about 1300LT.

Handa (1978) finds that the diurnal variation of the amplitude of the lunar semimonthly tide in fOF2 in Wakanaii and in Kokubunji, presents a maximum between 1800LT and 2000LT. This is a little later than the time we find for the maximum in Ebro and in Hamilton. Handa and Maeda (1978) calculate the diurnal variation of the amplitude and phase of the semimonthly lunar tide and found an amplification of the amplitude at about 0400LT and about 2000LT. This variation would be similar to the one we found in summer at both stations. Nevertheless the time of the maxima found by these authors is different from the ones of Ebro and Hamilton.

According to the results shown in fig. 4 a-d, the solar influence on the amplitude of the semimonthly lunar tide at Ebro and Hamilton might be explained by the difference of response to the electrostatic field between the daytime and nighttime ionosphere, due to the differenret ion production processes and ionospheric perfiles during day and during night, as suggested by Handa and Maeda (1978).

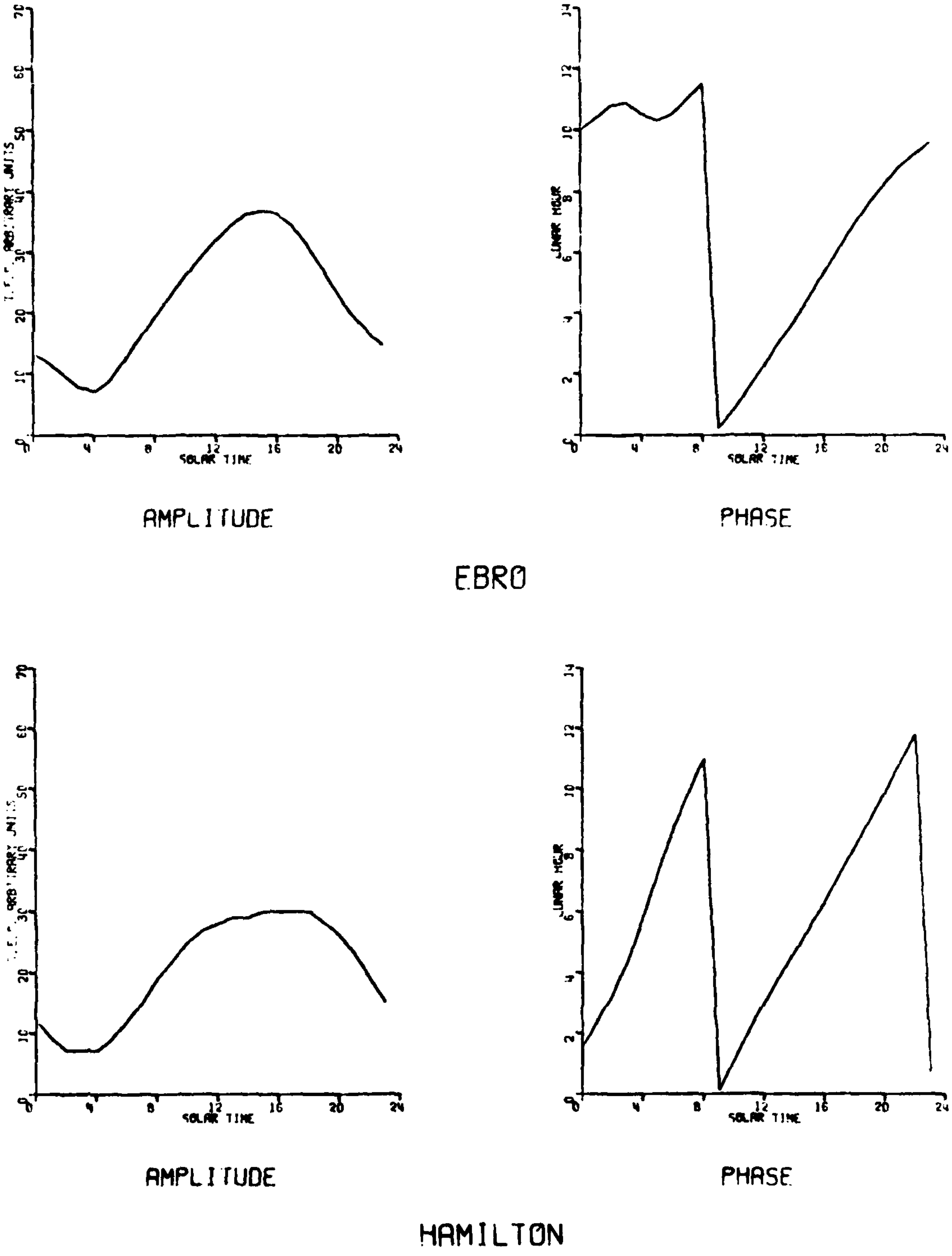


Fig.4a.- Solar variation of the semimonthly lunar tide. One year data.

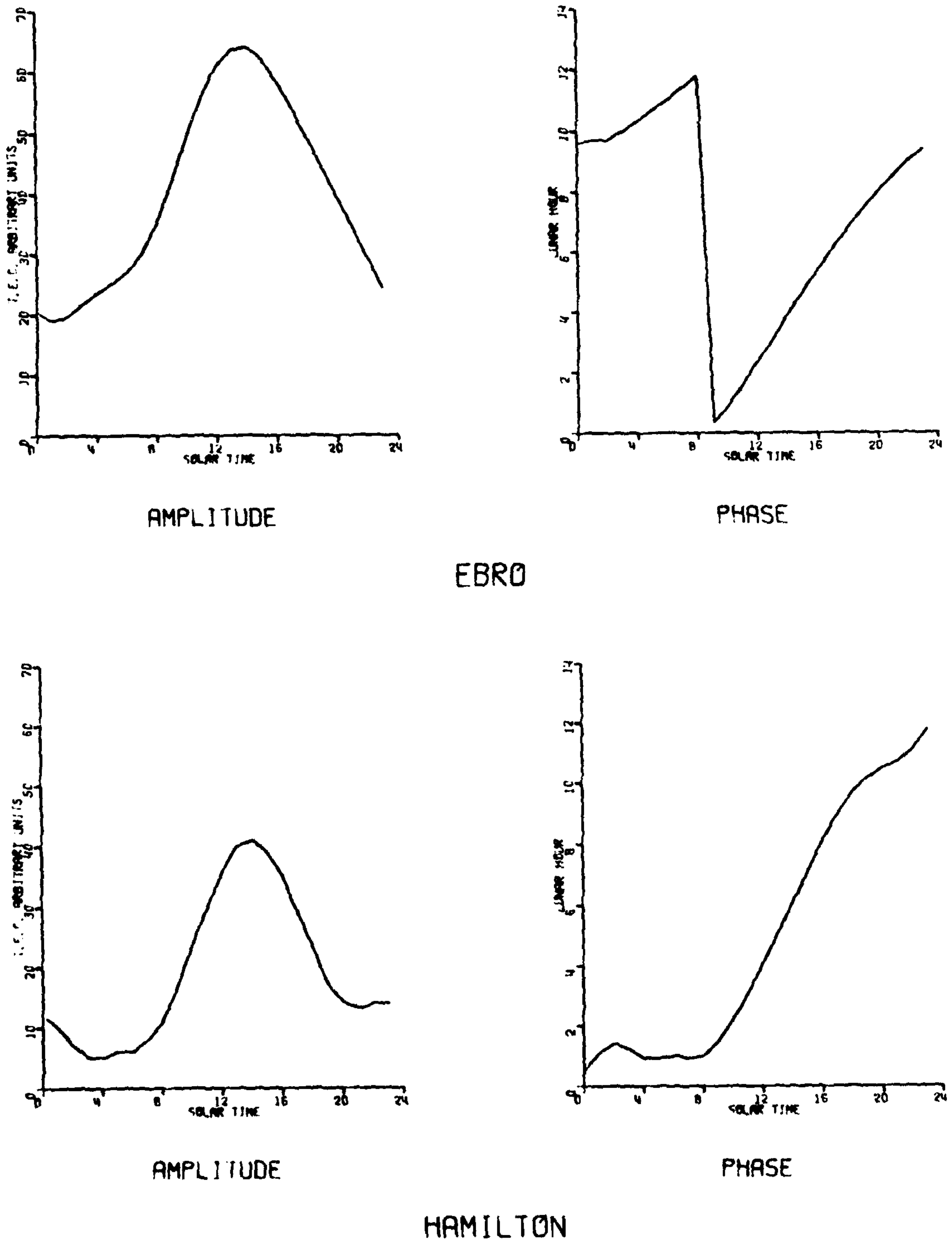


Fig.4b.- Solar variation of the semimonthly lunar tide.
Winter data.

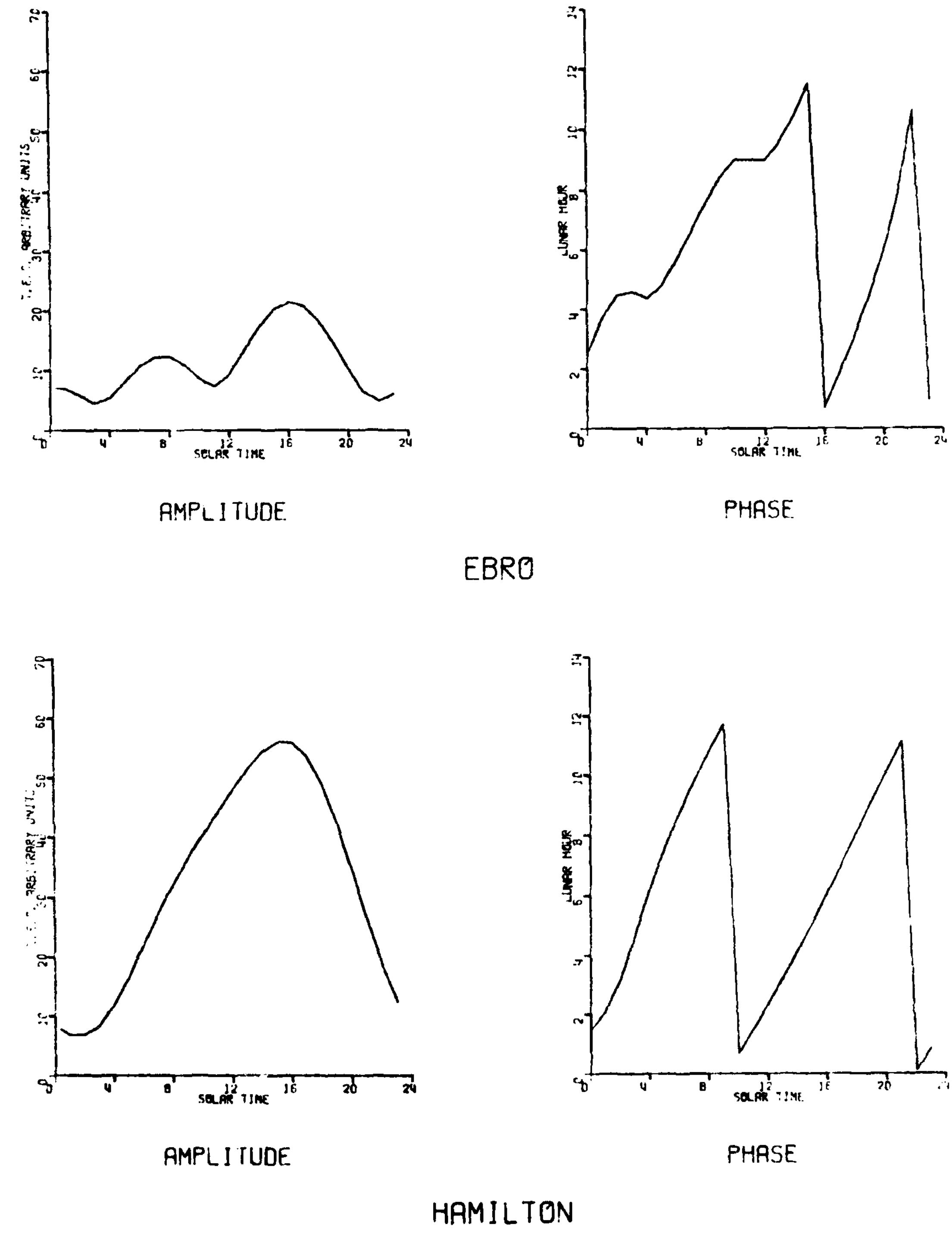
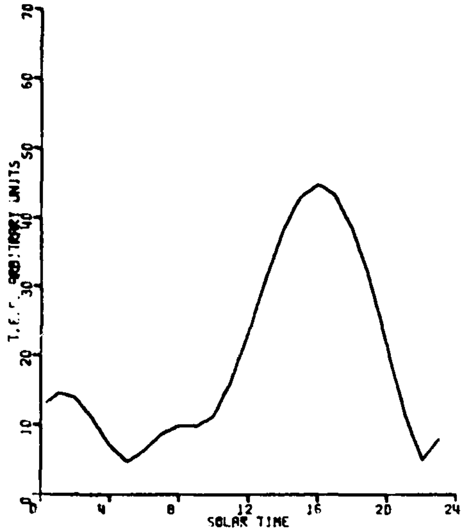
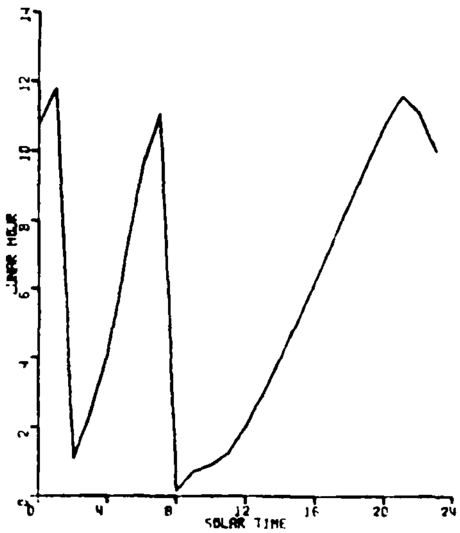


Fig.4c.- Solar variation of the semimonthly lunar tide.
Equinoxes data.

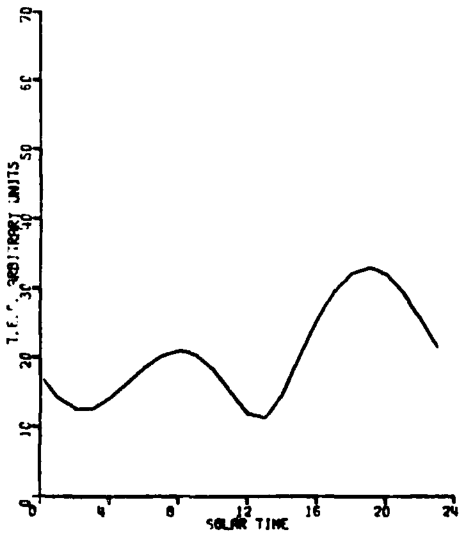


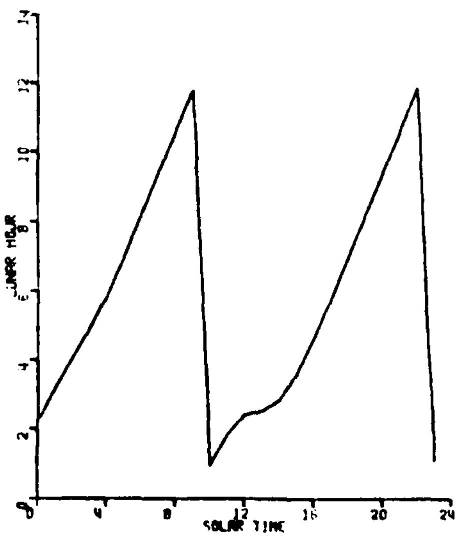


AMPLITUDE

PHASE

EBRO





AMPLITUDE

PHASE

HAMILTON

Fig.4d.- Solar variation of the semimonthly lunar tide. Summer data.

Phase.

As it can be seen in figs, 4 a-d, the phase of the semi-monthly lunar variation is usually zero at about 8h-10hr local solar time. There are only two exceptions: the curve of winter at Hamilton and the curve of equinoxes at Ebro. Nevertheless, the phase in the winter curve at Hamilton is very near zero at 8hr local solar time. On the other hand, the phase in equinoxes at Ebro has a zero value in the afternoon, between 15hr and 16hr local solar time.

Besides the zero of the 8hr-10hr local solar time. The phase in Hamilton takes again the zero value near the solar midnight.

At Hamilton, the phase has an almost constant increase for the whole day. The only exception is, again, the winter curve. In winter, it remains almost constant from 0hr to about 8hr local solar time with a value a little above zero. At about 8hr local solar time the phase begins to increase and at 23hr local solar time it reaches a value of about 12 lunar hours.

At Ebro, only the curves of equinoxes and summer have a second zero value of the phase near the solar midnight. At this station, the curves corresponding to the whole year and to winter are very similar. There is a small increase of the phase between 0hr and 9hr local solar time and a faster increase from this time onwards. In equinoxes, the increase of the phase during the first part of the day is also slower than the increase during the second part of it. In summer, on the contrary, the phase increases faster from 0hr to 8hr local solar time than during the rest of the day.

Comparing the curves of both stations, we see that the curves corresponding to winter have a similar variation, but the phase of Hamilton is delayed 1-3 lunar hours in relation to the phase of Ebro.

Also the curves of summer are very similar in both stations. From 5hr to 21hr local solar time the phases are

equal or the phase at Ebro is a little greater than the phase at Hamilton. For the rest of the day the phase at Hamilton is 2 or 3 lunar hours greater than at Ebro. The zero of the 8hr-10hr local solar time appears a little earlier at Ebro than at Hamilton. The midnight zero of the phase, that at Hamilton occurs at 22hr-23hr, at Ebro has been delayed to the early hours of the morning.

In equinoxes the phase variation at both stations is not so similar, but we have to keep in mind that the values for Ebro have been obtained from non significant results.

The results for the whole year sohw that the phase increa ses faster al Hamilton than at Ebro from 0hr to 8hr local solar time. From this hour onwards, the variation at both stations is almost the same.

CONCLUSION.

The semidiurnal lunar tide in TEC obtained by the Chapman-Miller method from Ebro data of the year 1978, shws an am plitude equivalent to the 2% of the mean yearly value and pha se of 10.5 lunar hours. Only the two first harmonics of the lunar tide are significant at the 5% level.

When the same method is applied to the Hamilton TEC data of the year 1976, the amplitude and phase obtained for the se midiurnal lunar tide are respectively 3% of the mean yearly value and 9.6 lunar hours. Here also only the two first harmo nics of the lunar tide are significant at the 5% level.

The results of the second harmonic are in agreement with results found by other authors ad midlatitudes.

If the data are grouped according to the different seasons, it is found that at Ebro only the two first harmonics in winter and the 2nd, 3rd and 4th harmonics in summer are significant at the 5% level. At Hamilton all but the first harmonic in summer are significant.

The second harmonic phase at Ebro is nearly the same in winter and in summer, while at Hamilton there is a small increase from the 8.2 lunar hours in winter to the 10.3hr in summer with an intermediate value of 9.7hr in equinoxes.

The non-significance of the equinoxes results at Ebro could be related to the change of position of the focus of the dynamo currents, as deduced from the diurnal variation of the horizontal magnetic component recorded at ground in Ebro.

The semimonthly lunar tide obtained from the lunar components found by the Chapman-Miller method, shows a solar dependence in both stations, Ebro and Hamilton. When the whole year is considered, the maximum amplitude is found to occur in the afternoon and the minimum in the early hours of the day. The maximum seems to shift towards later hours from winter to summer when the data are gathered in by seasons. This solar control of the amplitude of the semimonthly lunar tide is probably due to the different ion production processes and ionospheric profiles during day and night time. In general, the phase has a zero value at 8hr-10hr solar local time, and increases from this hour onwards. However in winter at Hamilton the phase remains almost constant, with a value a little above zero, from 0hr to 8hr solar local time and it begins to increase at this time. In the equinoxes at Ebro the phase takes the zero value at 15hr, but this result has been obtained from the non-significant data already mentioned.

All these results have to be taken as provisional since the number of data analized is not enough to obtain definitive conclusions. We intend to extend the analysis to more years in both, Ebro and Hamilton stations. With more data it will be possible to eliminate the disturbed days and more accurate results will be obtained.

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